Educational Neuroscience:

Neural Structure-Mapping and The Promise of Oscillations

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Abstract

A critical goal for educational neuroscience is to specify causal developmental mechanisms of learning. In-depth understanding of neural information coding and transmission should enable understanding of how sensory systems build the cognitive systems critical for education – language, attention, memory - over developmental time. Cortical oscillatory encoding processes may offer mechanistic insights into how developmental trajectories unfold. All educators are familiar with children who show mastery of taught information one week, yet subsequently appear to lose it. Oscillatory research shows that sensory information that arrives out of phase with ongoing oscillations does not reach awareness, while complex combinations of bottom-up and top-down phase-phase and phase-power relations enable context and prior knowledge to influence current performance. Oscillatory studies of language are used to illustrate the promise of oscillations research for education.

Highlights

- I discuss the promise of neural oscillations for specifying mechanisms of learning
- Cortical oscillatory encoding is explained and illustrated
- The role of oscillatory encoding in language learning is used as an example

Introduction

Infant research provides an important window onto the sensory mechanisms that support cognitive development [1,2]. Infants' sensory systems track statistical conditional probabilities from birth [3,4]. For example, the infant brain uses spatio-temporal structure to learn about higher-level domains such as agency and language (e.g., tracking biological versus mechanical motion to specify the animate-inanimate distinction, [5,6], see Figure 1; tracking energy modulations in the speech signal to help specify prosodic structure and where words begin [7, 8, 9, 10]). Meanwhile, neuroscience studies of basic sensory processing in adults help to specify how *prior experience* affects current perception. For example, when illusory sounds are perceived in noise (so that an attended sound is perceived as continuous, even though there is a noise during a *silent gap* in the attended sound), fMRI shows that the adult brain processes the *abstracted dependencies* of the basic properties of the sounds and the noise, rather than the acoustic properties of the *actual* sounds and noise experienced in that perceptual instance [11]. For adults and infants, prior learning of statistical dependencies in previously-experienced sensory inputs constrains current performance [12]. These statistical dependencies, extracted by instance-based learning, are recorded neurally during learning trajectories spanning long developmental time periods.

Figures 1 and 2 around here

Nevertheless, experience-dependent learning of statistical dependencies can be very rapid and (for auditory and tactile input) can be online in the womb [13]. By 3 months of age, infants can show sustained neural activity based on abstracted dependencies in the absence of sensory input. For example, by recording EEG during tests of infant understanding of 'object permanence' (the conceptual knowledge that objects continue to exist when they are out of view [14]), differences in neural activity were revealed when a hidden object's disappearance was *expected* versus *unexpected* given prior events [15] (Figure 2). Accordingly, sensory

processing of spatio-temporal statistical structure can *in principle* yield the abstracted dependencies traditionally discussed in cognitive developmental psychology as "prototypes" of concepts or as "causal knowledge" about physical systems [1, 16]. From a Bayesian perspective, these abstracted dependencies are statistical 'priors', the underlying building blocks that support complex cognition.

Neural Information Coding by Oscillatory Networks

Study of statistical 'priors' in educational neuroscience requires detailed specification of the statistical dependencies in the sensory input and of how these 'priors' support the development of the subsequent cognitive system. Oscillatory encoding mechanisms offer one means of specifying how these statistical dependencies are learned neurally. I will argue below that language is a cognitive system that now offers sufficient information about oscillatory mechanisms to support mechanistic educational neuroscience [17, 18, 19, 20, 21, 22, 23]. Meanwhile, detailed work in visual and auditory neuroscience reveals the richness and complexity of information representation possible via neural networks that oscillate quasi-rhythmically at different temporal rates [24, 25, 26, 27]. For example, when detecting visual targets, adults are unaware of visual stimuli that occur during the trough (least excitable phase) of a parietal alpha oscillation (~10 Hz), being most likely to detect targets at the oscillatory peak [28]. Visual events that arrive 'out of phase' do not reach conscious awareness. When adults monitor two spatial locations, then a theta-rhythmic process (~4 Hz) appears to alternately sample each location, with detection benefits alternating in a 4 Hz rhythm [29]. Here are obvious neural mechanisms to study developmentally in relation to individual differences in children's visuo-spatial attention [30] and visuo-spatial working memory [31]. Meanwhile, in audition and speech processing, theta is considered the primary temporal rate (the 'master oscillator' [32, 33]). Experimental studies with adults reveal that hierarchically-nested cortical oscillations at the rates of delta (~1 -3 Hz), theta (~4 – 8 Hz),

beta (~15 - 30 Hz) and gamma (>30 Hz) track naturalistic speech envelopes with high fidelity [34], with theta phase for example tracking syllable-level acoustic information [17] (a neural process called phase alignment or entrainment). The coherence of theta oscillations with the temporal speech envelope increases for adults when speech is intelligible (i.e., comprehended, eg [35]). The fidelity of bottom-up auditory entrainment [34,36] to the speech signal is thus an obvious target for investigating individual differences in language acquisition by infants. Meanwhile, oscillatory markers of the top-down mechanisms involved in speech comprehension (e.g., context, pragmatics) offer an obvious mechanism to study in relation to developmental oral language disorders.

Oscillatory Encoding and Rhythmic Temporal Sampling

Temporal rhythm is an important mechanism in encoding and transmitting sensory information, enabling the co-ordination of information within and across brain regions [37, 38, 39, 40]. Oscillating brain rhythms (the oscillations reflect the concentration of neuronal electrical discharges to particular phases of a temporal cycle) provide a means of controlling the *timing* of neuronal firing, enabling cell networks to "sample" sensory input *in parallel* in different temporal integration windows [37, 39, 41, 42, 43]. Neuronal spiking activity does not follow a smooth sinusoidal function (see Figure 3), rather *relative* neuronal firing times change dynamically as a function of stimulus properties, so that synchronised discharges of neurons phase-align (entrain) to incoming sensory information, or phase-align with activity in other oscillatory networks within and across cortical areas. This enables the precise and selective encoding and transmission of information [43].

Figure 3 around here

Similarly, zero-phase oscillatory synchrony (i.e. perfect temporal alignment of an oscillation across networks) is only one mechanism for synchronization, with small delays (e.g. of 2 - 20 ms) common in the nervous system [44]. Hence precise temporal intra-neural

co-ordination does not require a ‘master rhythm’ or metronome-like ‘master clock’ that follows a constant oscillation frequency [45]. Similarly, the environmental inputs themselves do not have to be perfectly periodic to be encoded successfully [46]. Nevertheless, there is usually quasi-rhythmicity in environmental inputs, which can support phase entrainment (e.g., *vision*: gait, wind-blown leaves; *audition*: birdsong, rain). Regarding environmental sounds like rain and wind, Turner [47] showed that Probabilistic Amplitude Demodulation (PAD) provided an effective Bayesian learning approach. Natural sounds are characterised by amplitude (local sound intensity) modulation patterns correlated over long time scales and across multiple frequency bands. As demonstrated below, an amplitude demodulation approach may enable characterisation of the statistical ‘priors’ that kick-start developmental trajectories for language learning. Note that *developmental* ‘priors’ may differ from the statistical dependencies revealed by studies of the developed (adult) system. Further, for the cognitive systems of *agency* and *language* respectively, communications with infants recruit a special code that exaggerates natural rhythmic cues in the input modality, namely *motionese* [48] and *Parentese* (infant-directed speech, IDS [8,49]).

The Nature of Learning Environments

Two further general insights are critically relevant to successful educational neuroscience. The first is that experience-dependent learning will differ across different *sensory systems*, with important consequences for the extraction of statistical dependencies. For example, while experience-dependent learning about the visual world is based on relatively rich input for all children (who all look at a visual world filled with motion, luminance changes and contrast cues), experience-dependent learning about the auditory world is based on varying input for different children. To the extent that the development of our conceptual systems (e.g., knowledge about categories and kinds) depends on seeing and experiencing the visual and tactile environment, then environmental differences between

children, even in Lapland versus the Sahara desert, will not be sufficient to cause large individual differences in developmental trajectories. However, the acquisition of language, arguably the most important driver of the cognitive systems critical for education, is based on environmental input that varies dramatically in both *quantity* and *quality* across children. In a classic study, linguistic input from age 0 – 4 years was estimated at 44 million utterances for high-SES children, and 12 million utterances for low-SES children [50]. Regarding the quality of the input, learning trajectories improve when infants hear a higher percentage of utterances in IDS [51].

Start States and End States

Secondly, in some cognitive domains the statistical dependencies that appear to describe the adult domain may not be those important at the *beginning* of sensory learning. Language processing is an obvious example. Entire fields of linguistic enquiry are based on the assumption that the 'phoneme' (the smallest sound element in a word that changes meaning) is the primary unit in linguistic processing [52]. Accordingly, the relatively fast gamma oscillations that are assumed to encode phonemic information are the focus of many neural developmental language studies [53,54,55]. Yet only literate brains develop phoneme-based language representations [56]. Further, the linguistic *task* matters: the syllable rather than the phoneme appears to be the primary unit in adult oral speech processing, with theta the 'master oscillator' [21, 32, 57, 58]. The primary oral speech processing unit for *infants and children* may be the stressed syllable [59, 60]. Although young infants show categorical perception (imposing phonetic *categories*, such as /p/ versus /b/, onto acoustic continua [61]), so do chinchillas, budgerigars and crickets [62]. These animals do not develop language systems. Indeed, infants appear to *begin* parsing the speech signal on the basis of the prosodic rhythm and stress cues exaggerated in IDS. Accordingly, developmental studies need to study delta and theta as well as gamma oscillations [9, 10]. Identifying the core abstracted

dependencies or statistical 'priors' in a given domain is absolutely critical for the enterprise of educational neuroscience.

The Statistical Dependencies in Child-Directed Speech

A core developmental role for the stressed syllable in language acquisition is supported by our statistical modelling of IDS and child-directed speech (CDS) [63, 64, 65, 66] (Figure 4). Using Turner's PAD approach among others, we characterised the acoustic statistical dependencies in English nursery rhymes. We developed two *Amplitude Modulation Phase Hierarchy* (AMPH) models, demonstrating the importance of perceptual sensitivity to patterns of AM in children's phonological development [63,64]. We found that the core statistical dependencies in CDS were described by 3 nested AM tiers in temporal rate bands corresponding to delta-, theta- and beta/low gamma-rate oscillations. Hand annotation of phonological units revealed that this AM hierarchy (centred on ~2 Hz, ~5 Hz and ~20 Hz AMs) yielded the linguistic phonological hierarchy of stressed syllables, syllables, and onset-rime units in the spoken CDS corpus [64]. Oscillatory cycles in each AM band enabled the identification of phonological units, with considerable success (the model identified 95%, 98% and 91% of stressed syllables, syllables, and onset-rime units respectively for rhythmically-timed nursery rhymes). One interpretation is that the statistical 'priors' in CDS comprise an acoustic hierarchy of AMs, a *nested relational structure*. This nested relational structure mirrors the nested phase and power relations between oscillating cell networks in auditory cortex [22]. Studies of IDS are ongoing, but also reveal a core role for delta-rate AMs [67]. Accordingly, the rhythms and rhymes of the nursery are developmentally adaptive. Delta rather than theta may be the 'master oscillator' at the beginning of phonological development.

Figure 4 and Table 1 around here

Cognitive Awareness of Phonology in Pre-Reading Children

In related cognitive work, we have shown that the emergence of 'phonological awareness' in children develops in a correspondingly hierarchical fashion, from larger to smaller units across languages [56]. These units also form a nested relational structure (Table 1). Children can reflect on and manipulate phonological units larger than the phoneme *before learning to read*. Most developmental studies focus on syllables and onset-rimes (to divide a syllable into onset-rime units, segment at the vowel, e.g., *str-ing, br-ing, s-ing*). There are relatively few studies of prosodic sensitivity (although see [68, 69]), however the infant literature shows implicit awareness of trochaic stress templates (the dominant *strong-weak* [SW] pattern of bisyllabic words) in languages like English and German by age 4 months [70]. Note that these phonological units correspond to the three acoustic tiers revealed by our AMPH modelling. AMs in the delta-, theta- and beta/low gamma rate bands are relevant to identifying the stress foot (protowords, SW or SWW groupings of syllables eg *MUmmy* or *PUSSycat*), the syllable, and the onset-rime. Accordingly, one possibility is that the infant brain entrains automatically to these acoustic statistical dependencies. The speech heard in the cradle (at least, for English-hearing infants) is rhythmically-regular speech dominated by delta-rate AMs [67].

Oscillatory Entrainment to Speech by Children with Dyslexia

Studies of children with developmental dyslexia illustrate the promise of this conceptual approach for educational neuroscience. Children with dyslexia have phonological impairments, at all linguistic levels – they show poor phonological awareness of stressed syllables, syllables, onset-rimes, and phonemes [56,60,71]. When we began studying oscillatory entrainment to speech in dyslexic children, we expected to find impairments in theta entrainment, the 'master oscillator'. Instead, we have found atypical oscillatory entrainment to rhythm and speech in the delta band [72]. Our EEG studies showed a *different preferred phase* in delta in participants with dyslexia, as well as less accurate speech

envelope encoding [73, 74, 75]. Accordingly, we proposed that sensory/neural difficulties in recovering prosodic structure from speech input could lie at the heart of the phonological deficit in dyslexia, across languages. A sensory/neural framework is offered by Temporal Sampling (TS) theory [71]. TS theory suggests that auditory sensory impairments present from birth affect language acquisition from the "get-go", affecting the accuracy of oscillatory entrainment to AMs < 10 Hz and hence contributing to the phonological impairments that characterise children with dyslexia across languages [60]. From this perspective, impaired phonological processing in dyslexia would originate in atypical delta-rate entrainment.

If supported by future studies across languages, these mechanistic neural insights would support remediation for dyslexia based on musical, motor and language rhythms focused on delta-band rates [76, 77]. Currently, there is little relevant literature, as many studies of oscillatory entrainment in dyslexia have not utilised speech stimuli [55,73,78]. Consequently, it remains to be determined whether the delta-rate impairment is developmentally primary, and whether the atypical gamma-rate entrainment reported for adult dyslexics in some studies [55,79] reflects their 20+ years of reduced reading experience [see 60]. In the only entrainment study to date to test *both* adults and children with dyslexia and to use speech stimuli (a sentence listening task in Spanish [80]), both groups showed impaired oscillatory entrainment in the delta band, with effects originating in primary auditory cortex. The authors concluded that reduced speech-brain synchronisation in the delta band appeared to be preserved in dyslexia through development from childhood to adulthood, with inevitable higher-order consequences across the speech processing network. The convergence of delta-band findings across Spanish (a syllable-timed language) and English (a stress-timed language [75]) supports the cross-language utility of TS theory.

Conclusions

Neural mechanisms of information coding and transmission based on cortical oscillations are highly relevant to the enterprise of educational neuroscience. This new field needs to go beyond demonstrating structure-function correlations to studying mechanisms of learning. Cognitive development depends in part on the brain extracting spatio-temporal statistical dependencies from environmental inputs in an automatic fashion, which is enabled across domains by oscillatory structure-mapping. Accordingly, optimal learning environments in infancy and childhood should support and develop the core 'statistical priors' in a given domain. The emergent knowledge systems based on these statistical dependencies can then be enriched and transformed by cultural learning and education.

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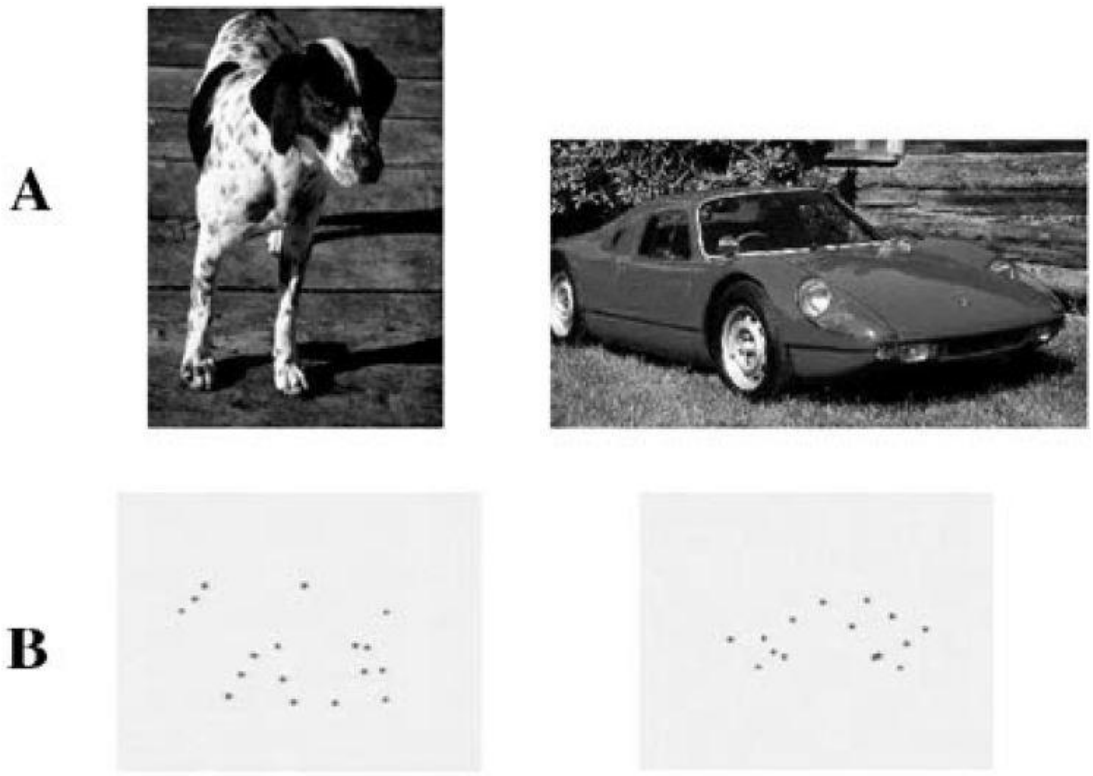
Table 1. **Acoustic-Neural Structure-Mapping**.

Phonological Level	Oscillatory Frequency (EEG band)	Example/s	Age at which reflective awareness develops
Intonational Phrase	~ 1 Hz and lower	Who's a pretty boy then?	Not yet ascertained
Stressed syllable	~ 2 Hz (delta)	PE-ter PI-per PICKED a PECK of PICK-led PEPP-ers	Not yet ascertained
Syllable	~ 5 Hz (theta)	an – i – mal wig – wam	2 – 3 years
Onset-rime	~ 20 Hz (beta)	c – at str – eam cl - amp	3 – 4 years
Phoneme	~ 35 Hz (gamma)	c – l – a – m - p	With alphabetic tuition

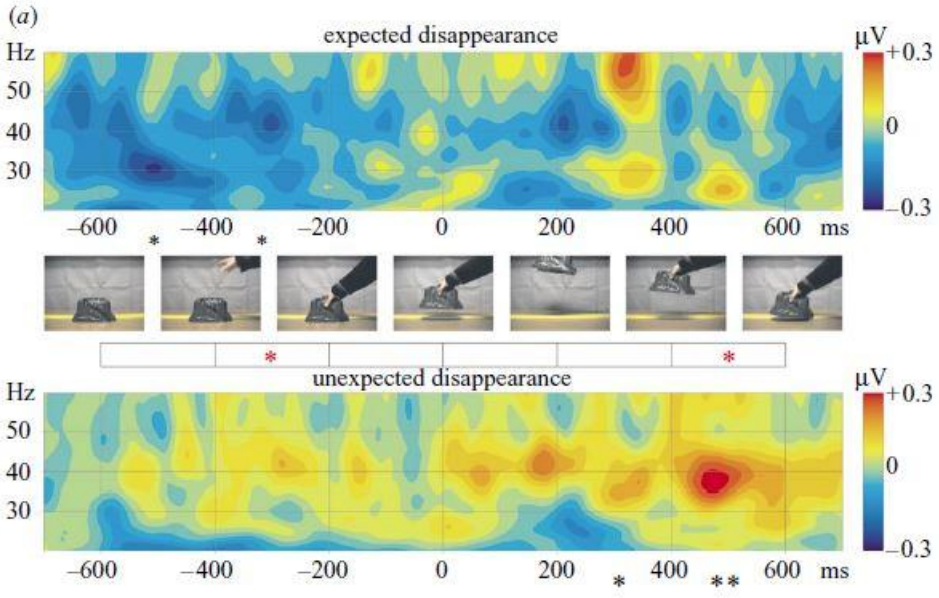
A linguistic identification of hierarchically-nested levels of phonology in the speech signal, adapted from [60], with corresponding oscillatory bands. In principle, accurate oscillatory entrainment to a corresponding AM hierarchy would enable phonological parsing via an automatic process of structure mapping.

Figure 1.



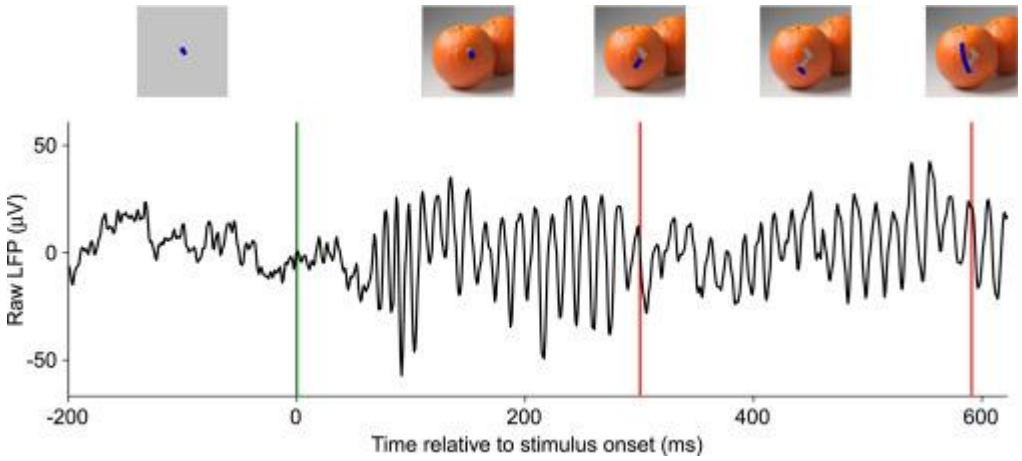
Spatio-temporal motion cues specify animacy. (A) Static images of exemplars from the animal and vehicle categories and (B) a single frame from the dynamic point-light displays of the dog and the sports car. [6]

Figure 2.



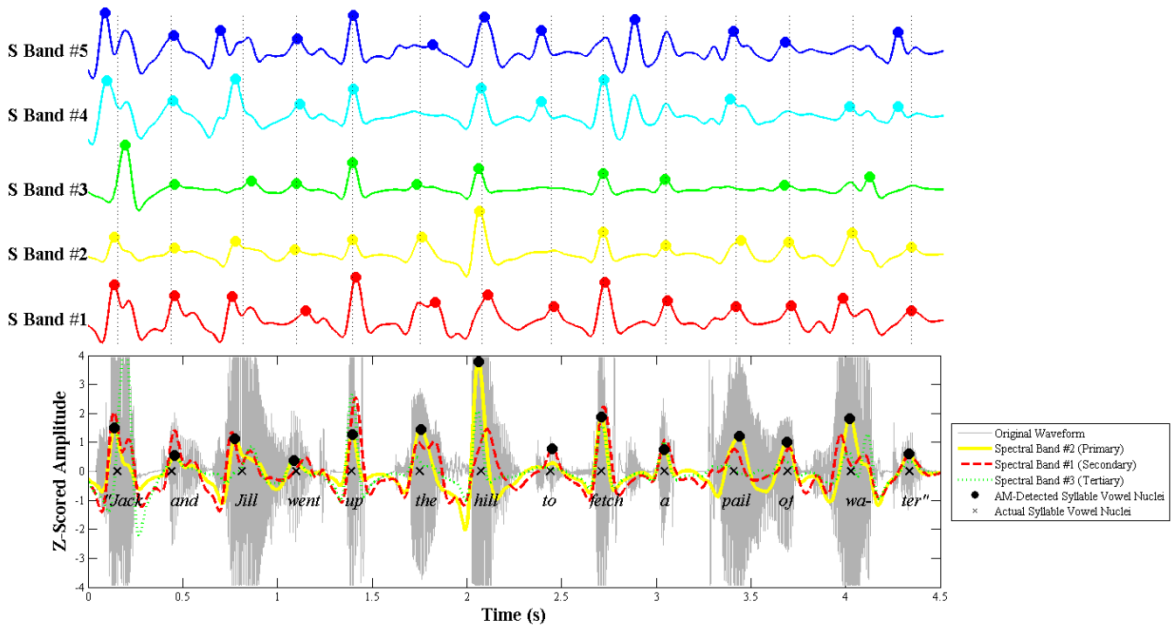
Sustained neural activity in the absence of sensory input in 3-month-old infants. Gamma-band activity: (*a*) Time–frequency analysis of the average EEG at three electrodes over the right temporal cortex (around T4) during the phase in which the tunnel was lifted showed higher activations when the object should have been below the tunnel. Black asterisks below the maps indicate a significant difference from baseline; red asterisks indicate a significant difference between conditions in the average gamma activity in 200 ms-long bins (*t*-tests: $*t_{21} > 2.00$, $p < 0.05$; $**t_{21} > 2.80$, $p < 0.01$).

Figure 3.



Gamma oscillation in monkey visual cortex during natural viewing. Raw Local Field Potential trace recorded as the voltage between two neighbouring electrocorticographic electrodes on primary visual cortex of an awake macaque monkey during one visual exploration of the photograph of two oranges (from [43]). Green vertical line indicates stimulus onset, red vertical lines indicate saccades. Insets show the stimulus and superimposed the eye position trace around that time point in blue, and the eye position trace during this exploration so far in gray. Prior to stimulus appearance and free viewing, the monkey fixated on a small central dot.

Figure 4.



Example of syllable finding by the Spectral Amplitude Modulation Phase Hierarchy Model (S-AMPH, [64]). The lowest panel shows the AM peaks corresponding to the syllables in the nursery rhyme 'Jack and Jill went up the hill' for the primary spectral bands (power ranked) in the S-AMPH model. Each spectral band is depicted in a different colour; the mid-frequencies for each spectral band are S Band #1 (red), 150 Hz, S Band #2 (yellow), 500 Hz, S Band #3 (green), 1225 Hz, S Band #4 (turquoise), 2825 Hz, S Band #5 (blue), 5575 Hz. The candidate peaks that were detected at these 5 AM rates are shown as coloured dots. The vertical dotted lines indicate the actual (manually-annotated) location of the syllable vowel nuclei in the sentence, while the black dots indicate the final selected Syllable AM peaks (=model-detected syllable vowel nuclei). As can be seen, the Syllable AM peaks in the primary spectral band (#2, yellow) correspond correctly to almost all the actual syllable vowel nuclei. Interestingly, the carrier in the psychoacoustic task (1 Rise task) used to demonstrate impaired rise time sensitivity in children with dyslexia across languages is 500 Hz (ie, centre frequency for S Band #2). This is supportive of impaired AM-based parsing of incoming speech at the syllable level in developmental dyslexia.